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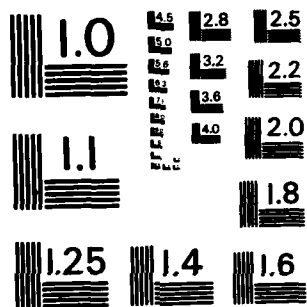
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received a large interest. This is manifested by the fact that already 25 researchers (from the academic and industrial worlds) have announced their intentions to "predict" the aeroelastic behavior of one or several of the experimental test cases. An absence of well documented experimental data have been found, noticable in the domain of high turning subsonic turbine blades and in the field of transonic/supersonic quasi-two-dimensional flat plate investigations. As regards to the high turning turbine blades, the Laboratoire de Thermique Appliquee has recently started such experimental work. The result of this investigation can be distributed, as a further test case, during 1983.

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Project No: AFOSR 81-0251

"AEROELASTICITY IN TURBOMACHINE-CASCADES"

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Second Semi-Annual Progress Report: March 1 - August 31, 1982

Submitted by

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Principal Investigator

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## SUMMARY

The aeroelastician needs reliable, efficient methods for the calculation of unsteady blade forces in turbomachines. The validity of such theoretical prediction models can only be established if researchers apply their flutter and forced vibration predictions to a number of well documented experimental test cases.

The purpose of the present work is to select a certain number of experimental standard configurations to be used as test cases for theoretical prediction models, as well as for other experiments.

A standardized nomenclature and reporting format, to be used for facilitation of comparisons in the present project, has been defined. The reporting format allows for both detailed comparison of the experimental and theoretical results, as well as for a direct judgment of the flutter tendencies of a specific turbomachine blading.

A large number (36) unsteady experimental data have been compiled, classified and evaluated. Out of these 36 data, 9 have been retained as possible test cases.

Also the theoretical part of the project has received a large interest. This is manifested by the fact that already 25 researchers (from the academic and industrial worlds) have announced their intentions to "predict" the aeroelastic behaviour of one or several of the experimental test cases.

The potential for a very positive result from this joint research work has become increasingly larger, as many more institutions than originally previewed are interested in the establishment of the validity of existing and future theoretical prediction methods for flutter and forced vibrations.

In total, 31 persons are participating in the experimental part and 25 in the theoretical. The participants are very evenly distributed throughout the Western countries with an interest in this field, namely 18 from the USA (7+11), 24 from Europe (16+8) and 14 from Japan (8+6).

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## 1. Introduction

In axial-flow turbomachines considerable dynamic blade loads may occur as a result of the interaction between the unsteady flow and the blades. The trend towards ever greater mass flows or smaller diameters in the turbomachines leads to higher flow velocities and to more slender blades. It is therefore likely that aeroelastic phenomena, which concerns the motion of a deformable structure in an airstream, will increase ever more in future turboreactors (fan stage) and industrial turbines (last stage).

The large complications, and high costs, of unsteady flow measurements in actual turbomachines makes it necessary for the aeroelastician to rely on cascade experiments and theoretical prediction methods for minimizing blade failures due to aeroelastic phenomena. It is therefore of great importance to validate the accuracy of flutter and forced vibration predictions and compare theoretical results with cascade tests and trends in actual turbomachines.

Several well documented unsteady experimental cascade data exists throughout the world, as well as many different promising calculation methods for solving the problem of unsteady flow in two-dimensional and quasi two-dimensional cascades. However, due to different basic assumptions in these methods, as well as many different ways of representing the obtained results, no real effort has been made to compare theoretical methods with each other. Further, the validity of these theoretical prediction analysis can only, since hardly any exact solution are known, be verified by comparison with experiments. This is very seldom done, partly because of the reasons mentioned above, partly as well documented experimental data normally are of proprietary nature.

It is the purpose of the present project to partly remedy the above mentioned situation.

This can be done by:

- (I) establish a data bank of test cases for off-design calculations

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- (II) initiate a workshop, in which specialists can compare and discuss their results
- (III) define precise reporting formats for representing the experimental and theoretical results
- (IV) initiate additional measurements on existing test facilities.

The final report of the present work will be presented at the "Third International Symposium on Aeroelasticity in Turbomachines", to be held in Cambridge, UK, 1984 (/9/, /10/)

## 2. PROGRESS IN THE PERIOD MARCH 1 - AUGUST 31, 1982

### 2.1 Compilation of experimental test cases

As described in detail in the first semi-annual progress report ([7]), most of the major institutions in the field of aeroelasticity, both in USA, Europe and Japan, are participating, in one way or another, in the present joint research work (see table 1). Out of the 34 sets of experimental data presented in table 1, the ones from

ONERA	(Girault)
ONERA	(Szechenyi)
TOKYO UNIVERSITY	(Tanaka)
DETROIT DIESEL	(Jay)
ALLISON	
UNITED TECHNOLOGIES	(Carta)
NASA LEWIS	(Boldman/Ball)
EPF-LAUSANNE	(Fransson/Schläfli)
EPF-LAUSANNE	(Fransson/Schläfli)
NATIONAL AEROSPACE LAB. TOKYO	(Kobayashi)

are still retained as possible test cases. The others have been eliminated due to one, or several, of the following criteria:

- In order to exploit to the maximum the comparison between theories and experiments, only a limited number of test cases, concerning fully aeroelastic phenomena in turbomachine-cascades, can be chosen.
- Eventually, rotor-stator interactions may be introduced in the present work at a later time.
- The state-of-art of calculation methods must be taken account of. Therefore, the scope of the present joint work will not include fully three dimensional experiments and calculations.
- The data (at least some preliminary) must be ready for distribution towards the end of 1982. The data from Whittle Laboratory, TH-Aachen and Toshiba-Kawasaki will unfortunately not fulfill this criteria.

 = Not appropriate

- 2-dimensional isolated airfoils.  
This problem is treated in an AGARD Workshop (1/1).

- 2-dimensional or quasi 2-dimensional aeroelastic investigations in linear cascades

- Quasi 2-dimensional aeroelastic investigations in annular cascades

- Fully 3-dimensional aeroelastic investigations in real machines.
- + No fully 3-D calculation methods exists presently, wherefore we have to wait this at a later time.

- \* Non-vibrating blades. Pressure fluctuations due to water inter-  
tions or acoustic resonances.
- \* In order to exploit to the maximum the comparison between different theories and experiments, a very restricted number of test cases concerning aerelastic phenomena will be chosen.
- \* We have however to investigate this theme at a later time.

- Exact solutions
- + Small perturbations

Institution	Name	Classification Number	Geometry			Flow regime	Flutter	Kinematics			Node	Results	Remarks																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
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**Table 1.** Classification of the 34 sets of experimental data and some exact solutions, from which the test cases will be chosen.

The scope of the present work is limited to two-dimensional or quasi two-dimensional configurations (sets A, C and F above).

- In the experiments, several parameters should be varied. This is not the case in a few tests directed primarily towards the establishment of flutter boundaries, although these tests may be, as in the case of the ones by Brown Boveri and Westinghouse, very well documented.
- The test cases should treat results from linear or annular cascades, not real machines or isolated airfoils, in order not to diverge the scope of the work.

One or two experimental test cases will be designed in each of the four main velocity ranges: incompressible, subsonic, transonic and supersonic. The compilation of these data are currently under way, and a report with this information ([8]) will be distributed to the participants for off-design calculations towards the end of 1982.

## 2.2 Definition of precise reporting formats for the experimental and theoretical results

In the above mentioned compilation of experimental data as test cases for off-design calculations ([8]), the first chapters treat the standardization of the aerodynamic nomenclature to be used by all participants in the present work. This is a very important factor, in order to facilitate the evaluation and validation of, as well as the comparison between, the experimental and theoretical results.

A minimal number of prescriptions should of course be used in a joint work of the present type. However, the main nomenclature must be standardized in order to avoid misunderstandings and to facilitate the comparison of relevant information. The notations recommended are based upon the ones in references [1] to [6], and especially on the work by Carta ([1], [5]).

### 2.2.1 Steady Two-Dimensional Cascade Nomenclature

The profiles under investigation are arranged, in a two-dimensional section of the cascade, as in Fig. 1. In this figure, all the physical lengths are scaled with the chordlength "c", and the nomenclature in table 2 is used.

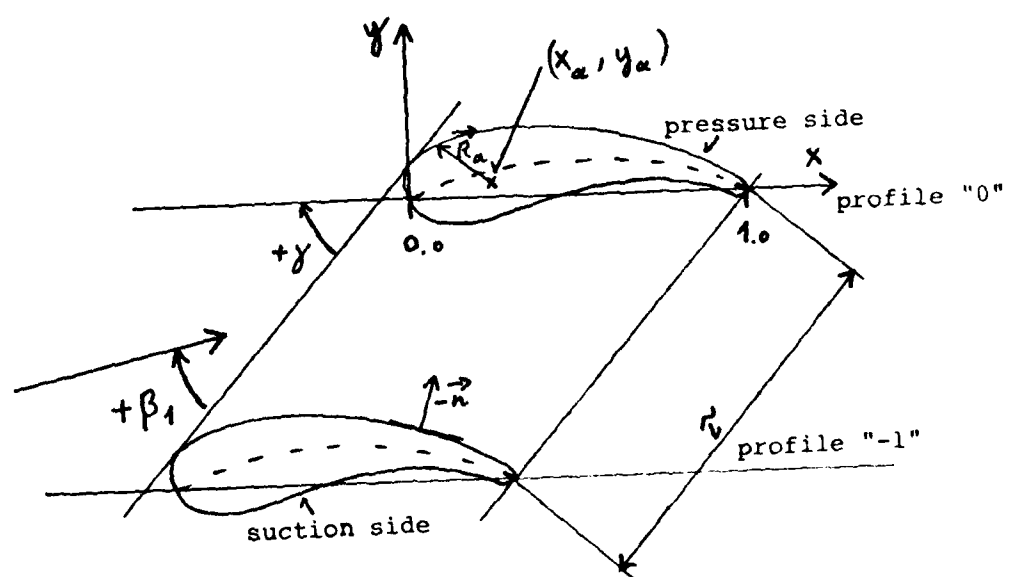


Fig. 1 Steady two-dimensional cascade nomenclature

SYMBOL	EXPLANATION	DIMENSION
$c$	chord length	m
$\bar{c}_p$	time averaged pressure coefficient	-
$i$	incidence angle	deg
$M$	Mach number	-
$\vec{n}$	unity vector normal to blade surface, positive inwards	-
$p$	pressure	N/m <sup>2</sup>
$\vec{R}_a$	dimensionless vector from mean pivot axis to an arbitrary point on the mean blade surface	-
$\vec{s}$	unity vector tangent to blade surface, positive in positive coordinate directions	-
$V$	velocity	m/sec
$x$	dimensionless chord-wise coordinate	-
$y$	dimensionless normal-to-chord coordinate	-
$\beta$	flow angle	deg
$\gamma$	chordal stagger angle	deg
$z$	dimensionless blade pitch	-

## Subscripts

$G$	center of gravity
$t$	total head value
$\alpha$	pitch axis (see Fig. 1)
$x$	component in x-direction
$y$	component in y-direction
$1$	measuring station upstream of cascade
$2$	measuring station downstream of cascade
$-\infty$	values at "infinity" upstream
$+\infty$	values at "infinity" downstream

## Superscripts

$(m)$	mth blade, $m=0, \pm 1, \pm 2, \dots$ . If the amplitudes, interblade phase angle, ... are constant for the blades under consideration, this superscript will not be used.
$(ps)$	pressure surface of profile
$\sim$	steady (=time averaged) values. This superscript will only be used in ambiguous context.
$(ss)$	suction surface of profile
$-$	amplitude of complex value

TABLE 2

Steady two-dimensional cascade nomenclature

### 2.2.2 Unsteady Two-Dimensional Cascade Nomenclature

#### Blade Motion

Fig. 2 is a schematic representation of cascaded two-dimensional airfoils; the form of the section is considered to remain rigidly fixed during heaving and/or pitching oscillations ( $\vec{h}(x,y,t)$  and  $\vec{\alpha}(t)$ , resp. ). The components  $h_x$ ,  $h_y$  and  $\bar{\alpha}$  of the motion vectors  $\vec{h}$  and  $\vec{\alpha}$  are noted in complex form to account for phase differences between the translations in x and y-directions as well as the rotation:

$$\text{heaving : } \vec{h}^{(m)}(x,y,t) \equiv \vec{h}^{(m)}(x,y) e^{i\omega^{(m)}t} \quad (1a)$$

$$\text{pitching } \vec{\alpha}^{(m)}(t) \equiv \vec{\alpha}^{(m)} e^{i\{\omega^{(m)}t + \theta_{\alpha}^{(m)}\}} \quad (1b)$$

It is here assumed that the torsional motion, for the (m)th blade, preceeds the bending motion by a phase angle  $\theta_{\alpha}^{(m)}$ . Further, if the vibration frequency is identical for all blades, the superscript (m) on  $\omega^{(m)}$  will be dropped.

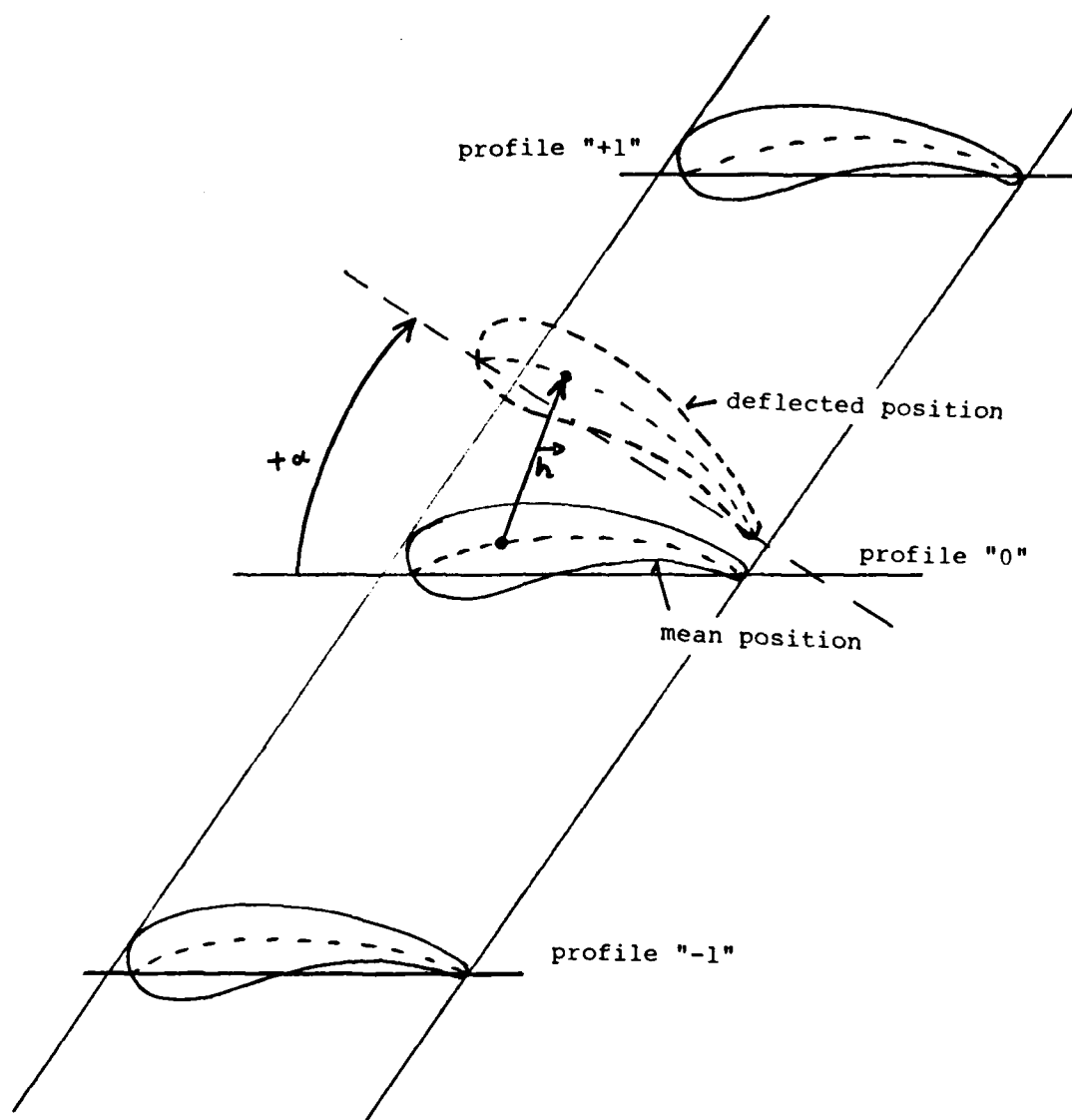


Fig. 2 Unsteady two-dimensional cascade nomenclature



### Two-Dimensional Aerodynamic Coefficients

The unsteady (complex) blade surface pressure coefficient, as well as the lift, force and moment coefficients, are scaled with the amplitude of the corresponding motion (amplitude = A, where  $A \equiv \bar{h}^{(m)}$  or  $\bar{\alpha}^{(m)}$ ).

$$\bullet c_{p_A}^{(B)}(x, t) = \frac{1}{A} \cdot \left\{ \frac{p^{(B)}(x, t) - p_{\infty}}{p_{t\infty} - p_{\infty}} \right\} \quad (2)$$

$$\begin{aligned} \bullet c_{L_A}(t) &= \frac{1}{A} \cdot \frac{1}{p_{t\infty} - p_{\infty}} \cdot \oint_{\text{profile surface}} p(x, t) \{ \vec{n} \cdot \vec{e}_y \} ds = \\ &= \int_0^1 \left\{ c_{p_A}^{(ps)}(x, t) - c_{p_A}^{(ss)}(x, t) \right\} dx \quad (3) \end{aligned}$$

$$\bullet \vec{c}_{FA}(t) = \frac{1}{A} \cdot \frac{1}{p_{t\infty} - p_{\infty}} \cdot \oint_{\text{profile surface}} p(x, t) \cdot \vec{n} dx \quad (4)$$

$$\bullet c_{M_A}(t) = -\frac{1}{A} \cdot \frac{1}{p_{t\infty} - p_{\infty}} \cdot \oint_{\text{profile surface}} \left\{ \vec{r}_a \times (p(x, t) ds \vec{n}) \right\} \cdot \vec{e}_z \quad (5)$$

where

- force components are positive when acting in positive coordinate directions.
- $c_M$  is positive when acting in clockwise direction
- (B) (superscript) denotes the blade pressure surface (ps) or blade suction surface (ss).

A further important quantity, for slender blades, is the dimensionless pressure difference on the blade,  $\Delta c_p$ . This is defined as the difference between the pressures on the blade pressure and suction surfaces:

$$\bullet \Delta c_p(x, t) = \{c_p^{(ps)}(x, t) - c_p^{(ss)}(x, t)\} \quad (6)$$

All of the above mentioned variables can be expressed in either complex exponential form or in component form as:

$$\bullet c_p(x, t) = \bar{c}_p(x) e^{i\omega t + \phi_p(x)} = \quad (7a)$$

$$= \{c_{pR}(x) + i c_{pI}(x)\} e^{i\omega t} \quad (7b)$$

Here, the subscripts "R" and "I" denotes the real and imaginary parts of the pressure coefficient  $c_p$ . Physically, these two parts can be interpreted as the components of the pressure coefficient which are in-phase (real part) and out-of-phase (imaginary part) with the blade vibration. Further, the phase angles  $\phi_p(x)$ ,  $\phi_{\Delta p}(x)$ ,  $\phi_L$ ,  $\phi_F$ ,  $\phi_M$  are all defined positive when the pressure (pressure difference, lift, force or moment, resp.) leads the motion.

The amplitude and phase relationships in eq. (7) are defined in the usual manner, that is:

$$\bullet \begin{cases} \bar{c}_p(x) = \sqrt{c_{pR}(x)^2 + c_{pI}(x)^2} \\ \phi_p(x) = \tan^{-1} \{c_{pI}(x)/c_{pR}(x)\} \end{cases} \quad (8a)$$

$$\bullet \begin{cases} c_{pR}(x) = \bar{c}_p(x) \cos \phi_p(x) \\ c_{pI}(x) = \bar{c}_p(x) \sin \phi_p(x) \end{cases} \quad (8b)$$

It should here be noted that, in computing the blade surface pressure distribution, only components, and not amplitudes or phase angles may be differentiated ( $|1|$ ). Therefore

$$\bullet \begin{cases} \Delta C_{PR} = C_{PR}^{(ps)} - C_{PR}^{(ss)} \\ \Delta C_{PI} = C_{PI}^{(ps)} - C_{PI}^{(ss)} \end{cases} \quad (9a)$$

but

$$\bullet \begin{cases} \overline{\Delta C_p} \neq \overline{C_p^{(ps)}} - \overline{C_p^{(ss)}} \\ \phi_{\Delta p} \neq \phi_p^{(ps)} - \phi_p^{(ss)} \end{cases} \quad (9b)$$

#### Two-Dimensional Aerodynamic Work

The two-dimensional differential work done on a rigid system by the aerodynamic forces and moments is conventionally expressed by the product of the real parts ( in phase with motion components) of force and differential translation, as well as moment and differential torsion. Thus, the total aerodynamic work coefficient per period of oscillation, done on the system is obtained by computing

$$\bullet C_w = C_{w_h} + C_{w_\alpha} + C_{w_{h,\alpha}} \quad (10)$$

where

$$\bullet \left\{ \begin{aligned} C_{w_h} &= \oint_{\text{cycle of oscillation}} \operatorname{Re} \{ \bar{h} \vec{C}_{F_h}(t) \} \cdot \operatorname{Re} \{ d\vec{h}(t) \} & (11a) \\ C_{w_\alpha} &= \oint_{\text{cycle of oscillation}} \operatorname{Re} \{ \bar{\alpha} C_{M_\alpha}(t) \} \cdot \operatorname{Re} \{ d\vec{\alpha}(t) \} & (11b) \\ C_{w_{h,\alpha}} &= \oint_{\text{cycle of oscillation}} \left[ \operatorname{Re} \{ \bar{\alpha} \vec{C}_{F_\alpha}(t) \} \cdot \operatorname{Re} \{ d\vec{h}(t) \} + \right. & (11c) \\ &\quad \left. + \operatorname{Re} \{ \bar{h} C_{M_h}(t) \} \cdot \operatorname{Re} \{ d\vec{\alpha}(t) \} \right] \end{aligned} \right.$$

In the case of pure sinusoidal normal-to-chord bending or torsional vibration, as well as sinusoidal lift and moment responses, respectively, the expressions (11) may be integrated into the following simple formulas

$$\bullet \left\{ \begin{aligned} C_{w_h} &= \pi \bar{h}^2 C_{LI} (= \pi \bar{h}^2 \bar{C}_L \sin \phi_L) \\ C_{w_\alpha} &= \pi \bar{\alpha}^2 C_{MI} (= \pi \bar{\alpha}^2 \bar{C}_M \sin \phi_M) \end{aligned} \right. \quad (12)$$

The airfoil damps therefore the motion when the imaginary part of the lift and moment coefficients, resp. is negative.

An aerodynamic damping parameter  $\Xi$  is defined in references [1], as, with the same assumption as in (11),

$$\bullet \left\{ \begin{aligned} \Xi_h &= -C_{w_h} / \pi \bar{h}^2 = -C_{LI} \\ \Xi_\alpha &= -C_{w_\alpha} / \pi \bar{\alpha}^2 = -C_{MI} \end{aligned} \right. \quad (13)$$

This parameter is therefore positive for a stable motion.

### Non-Harmonic Pressure Response

All theoretical prediction methods for flutter and forced vibrations available today make a few basic assumptions.

Most of these methods are submitted to restrictions regarding

- sinusoidal blade vibrations
- sinusoidal pressure responses
- identical vibration frequencies for all blades
- identical vibration amplitudes for all blades
- constant interblade phase angles

In experiments, however, these assumptions can never be exactly fulfilled. The large energy input needed to drive a cascade with prescribed frequencies, amplitudes and phase angles makes it impossible to satisfy the three latter assumptions, apart from tests with low frequencies and/or small amplitudes. Even in this case though the pressure response on the profiles will, in generally, not be sinusoidal.

In the computation of the aerodynamic work and damping coefficients, this non-sinusoidal pressure response on the vibrating blades can still be used relatively easy, as it can be shown that only the frequency of the pressure response spectra that corresponds with the blade vibration frequency contribute to the aerodynamic work.

However, non-identical blade vibration amplitudes and interblade phase angles may largely contribute to some discrepancies between the experimental and theoretical results.

A detailed comparison and evaluation of unsteady experimental and theoretical cascade results necessitate thus a knowledge of the actual time histories of the experiments.

From these time-recordings, a statistical evaluation, or a Fourier analysis can be used to appreciate how well the different idealizations in the prediction models approximate the real physical conditions.

In the final comparison between the experimental and theoretical results, such an evaluation will therefore, if it exists for the experiment under consideration, be presented.

### 2.2.3 Definition of precise reporting formats

It is obvious that no universal representation of the flutter phenomena can be defined as long as the underlying physical reasons for the self-excited vibrations are not understood. Secondly, different importance is attached to different purposes of the experimental and theoretical investigations. It is evident that a designer of a turboreactor or industrial turbomachine is not interested in the same details of the aeroelastic phenomena as an experimentalist, who is performing tests in, for example, an annular cascade. Further, a numerical analyst has another sort of problem (mesh generation, accuracy...) and tend therefore to present his results in a way to facilitate comparisons with other theoretical approaches.

One of the main objectives of the investigations for both experimentalists and theoreticians is, of course, to furnish the designer of turbomachines with enough information to enable him to minimize blade failures due to aeroelastic phenomena. However, such a universal method is still years to come. The representations used in the present comparative work will therefore allow for evaluations and illustrations between

- experimental - experimental results
- experimental - theoretical results
- theoretical - theoretical results

It will also give a possibility of direct comparison of the flutter tendencies of the different cascades under investigation.

Thus, two different reporting formats of the results will be used:

- I The first part is directed towards the comparison and establishment of validity of theoretical models (and the experimental result). It will also indicate a quantitative comparison between the steady and unsteady blade forces.
- II The second part concerns the direct use of the data for establishing of the flutter boundaries.

In both cases, the exact representation will largely depend upon the existing experimental data.

Further to these representations, every participant is asked to present his data in any other way he judges useful for better physical understanding of the flutter phenomena.

#### I Detailed comparison of experimental results and theoretical approaches

The establishment of the validity of both experimental and theoretical results can only be done by a mutual agreement between the measured and calculated blade pressure distributions. This detailed comparison between experiments and theories will therefore be done on the basis of diagram 1, which will be presented for a few different combinations of

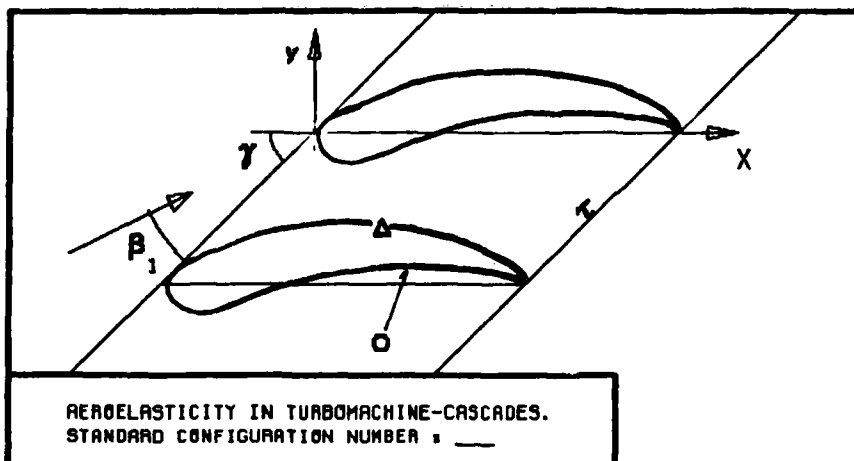
- interblade phase angle
- reduced frequency
- inlet conditions
- cascade geometry

depending upon the existing experimental data for the test case under investigation.

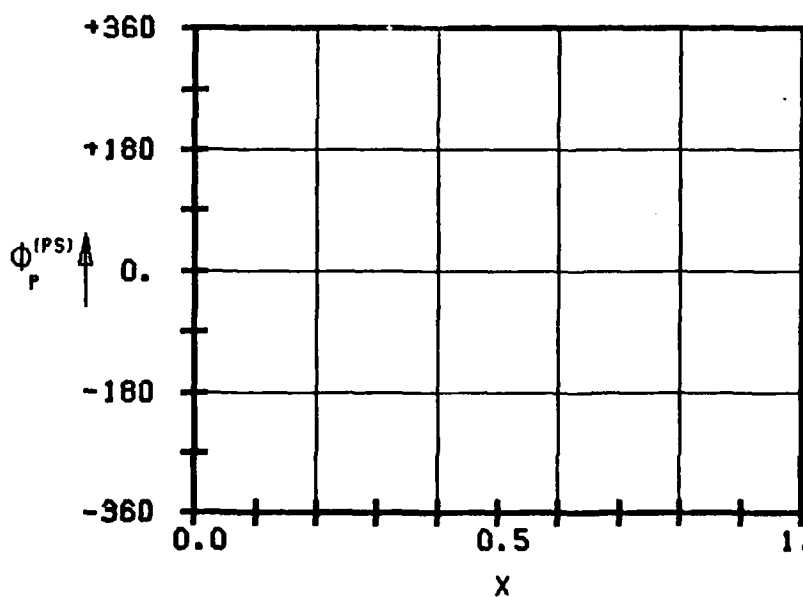
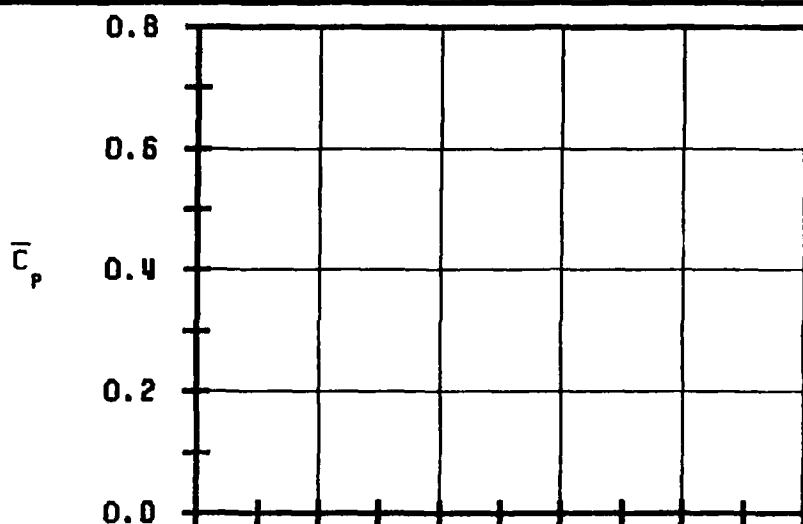
Quite a few prediction models for flutter or forced vibrations are based upon small perturbation theories, which means that the steady pressure distribution on the blade must be given as an input data. In this diagram 1, the time-averaged blade pressure distribution will therefore be specified for such studies.

Further, the comparison between the steady and unsteady blade pressure distributions may in some cases give a quantitative notion about the aeroelastic phenomena under investigation (instabilities due to stall, choke, shock... , coupling effects between the steady and unsteady flow fields).

The difference of the pressure coefficients,  $\Delta c_p(x)$ , along the blade indicates the distribution of the stable and unstable parts of the blades. This coefficient is therefore also of interest, and will be plotted in diagram 2.



AEROELASTICITY IN TURBOMACHINE-CASCADES.  
STANDARD CONFIGURATION NUMBER : —



C : 20

$\tau$  :

$\gamma$  :

$X_\alpha$  :

$Y_\alpha$  :

$M_1$  :

$\beta_1$  :

$M_2$  :

$\beta_2$  :

$\bar{h}_x$  :

$\bar{h}_y$  :

$\alpha$  :

$\omega$  :

K :

$\delta$  :

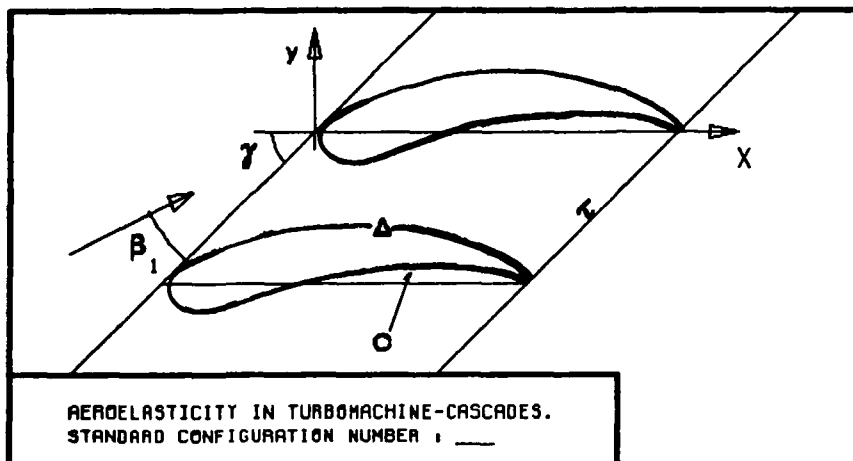
STABLE

UNSTABLE

STABLE

UNSTABLE

DIAGRAM 1 B : MAGNITUDE AND PHASE LEAD OF PRESSURE  
COEFFICIENT ON THE BLADE.



C : 21

$\tau$  :

$\gamma$  :

$X_a$  :

$Y_a$  :

$M_1$  :

$\beta_1$  :

$M_2$  :

$\beta_2$  :

$\frac{h}{h_x}$  :

$\frac{h}{h_y}$  :

$R$  :

$\omega$  :

$K$  :

$\delta$  :

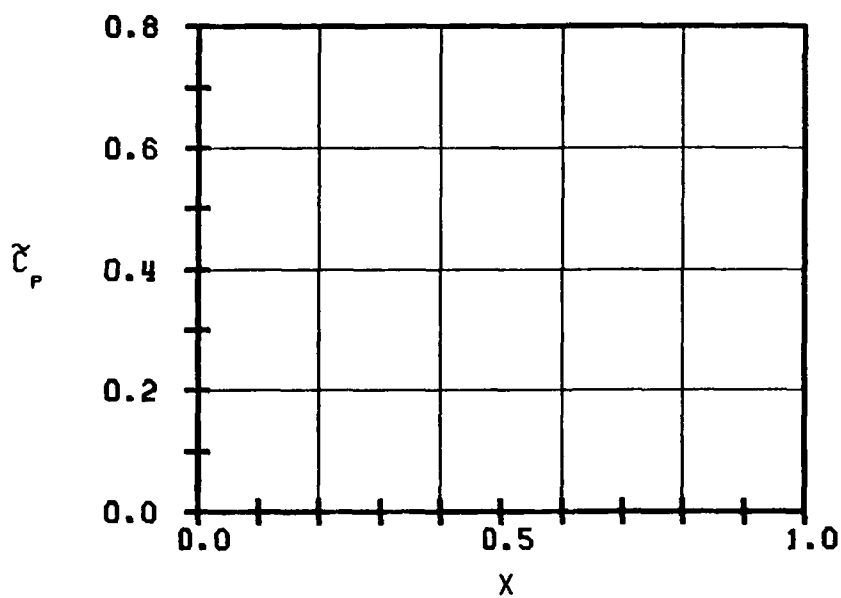
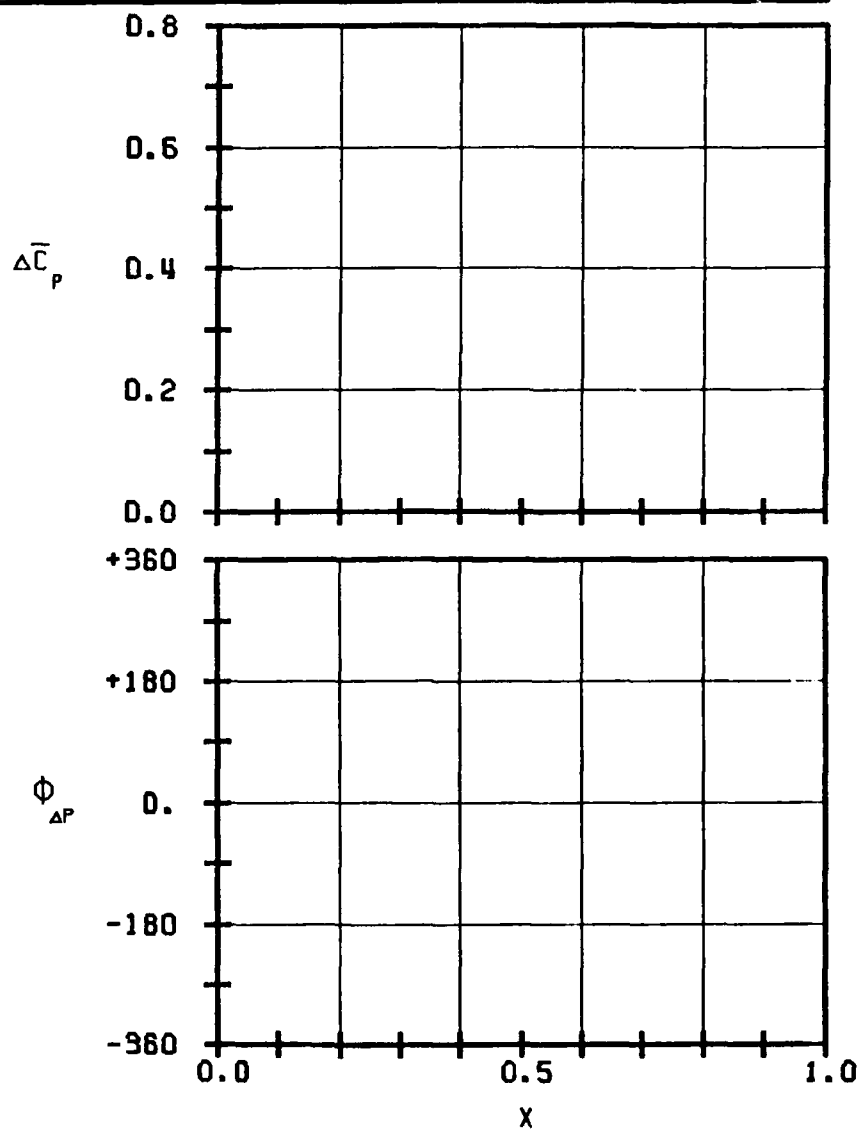
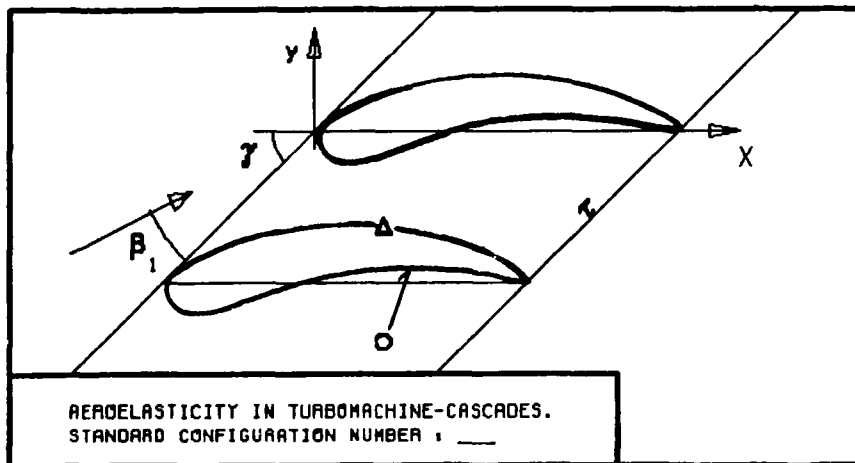


DIAGRAM 1 A : STEADY BLADE PRESSURE COEFFICIENT.



C : 22  
 $\tau$  :  
 $\gamma$  :  
 $X_\infty$  :  
 $Y_\infty$  :  
 $M_1$  :  
 $\beta_1$  :  
 $M_2$  :  
 $\beta_2$  :  
 $\frac{h}{h_X}$  :  
 $\frac{h}{h_Y}$  :  
 $\alpha$  :  
 $\omega$  :  
 $K$  :  
 $\delta$  :

STABLE

UNSTABLE

STABLE

UNSTABLE

DIAGRAM 2 : MAGNITUDE AND PHASE LEAD OF PRESSURE  
DIFFERENCE COEFFICIENT ON THE BLADE

## II. Flutter boundaries

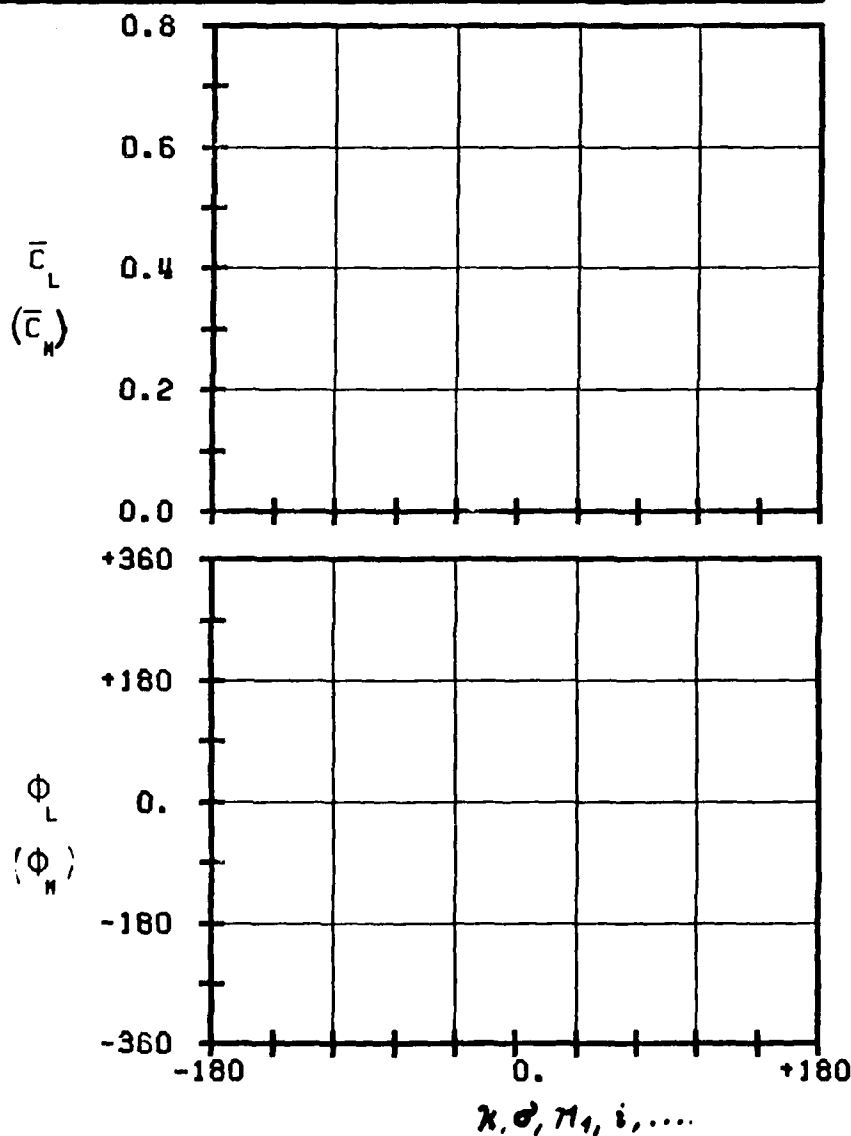
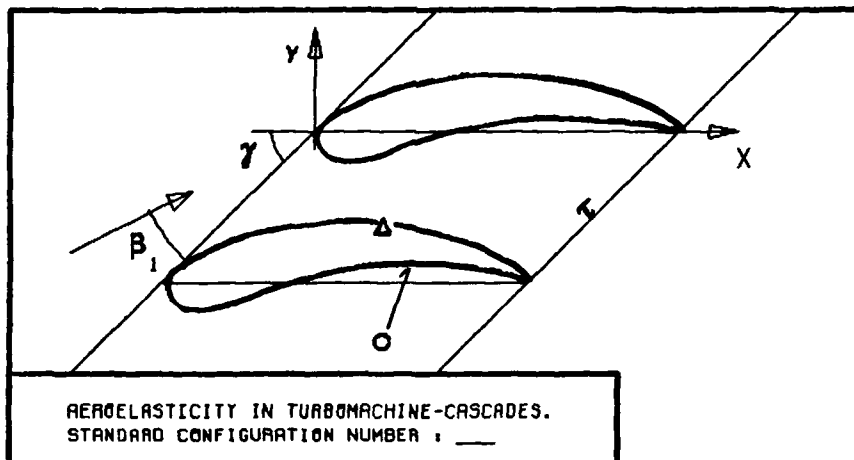
This second illustration concerns the integrated values of the aerodynamic blade forces and moments, as well as the aerodynamic work and damping coefficients.

Two different representations (see diagram 3 and 4) will be used to elaborate the flutter dependancies of several important parameters

- reduced frequency :  $k$
- interblade phase angle :  $\delta$
- inlet flow velocity :  $M_1$
- inlet flow angle :  $\beta_1$
- outlet flow velocity :  $M_2$
- cascade geometry :  $\gamma, \tau, c$ , profile

First, the unsteady blade pressure coefficients will be integrated to yield the aerodynamic lift and moment coefficients as in diagram 3. The phase angles  $\phi_L$  and  $\phi_M$  resp., give then directly information about the aeroelastic stability of the system (see chapter 2.2.2).

Secondly, the aerodynamic work and damping coefficients per cycle of oscillation may be calculated if the mode-shape of the motion is well known. Most of the problems treated in the present work will concern rigid systems (at least for the theoretical predictions), wherefore the aerodynamic damping coefficient can be easily computed and plotted. This coefficient is the single most interesting in judging the aeroelastic behaviour of a specific cascade, and should therefore be plotted for the benefit of the turbomachine designer.

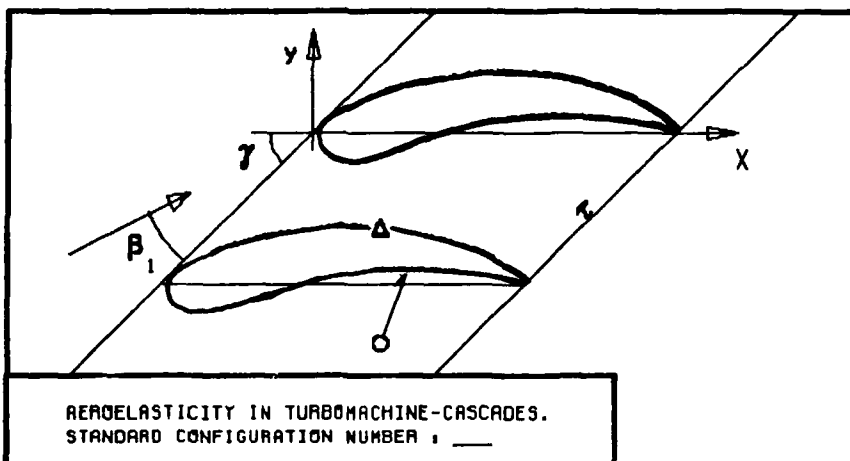


$C$  :  
 $\tau$  :  
 $\gamma$  :  
 $X_\alpha$  :  
 $Y_\alpha$  :  
 $M_1$  :  
 $\beta_1$  :  
 $M_2$  :  
 $\beta_2$  :  
 $\frac{h_x}{h_y}$  :  
 $\frac{h_y}{h_x}$  :  
 $\alpha$  :  
 $\omega$  :  
 $K$  :  
 $\delta$  :

\_\_\_\_\_  
 STABLE  
 \_\_\_\_\_  
 UNSTABLE  
 \_\_\_\_\_  
 STABLE  
 \_\_\_\_\_  
 UNSTABLE  
 \_\_\_\_\_

DIAGRAM 3 :

AERODYNAMIC LIFT (MOMENT) COEFFICIENT  
 AND PHASE LEADS IN DEPENDANCE OF FLOW  
 QUANTITIES AND CASCADE GEOMETRY.



AEROELASTICITY IN TURBOMACHINE-CASCADES.  
STANDARD CONFIGURATION NUMBER : \_\_\_\_\_

C : 25

$\tau$  :

$\gamma$  :

$X_\infty$  :

$Y_\infty$  :

$M_1$  :

$\beta_1$  :

$M_2$  :

$\beta_2$  :

$\frac{h}{h_x}$  :

$\frac{h}{h_y}$  :

$\alpha$  :

$\omega$  :

K :

$\delta$  :

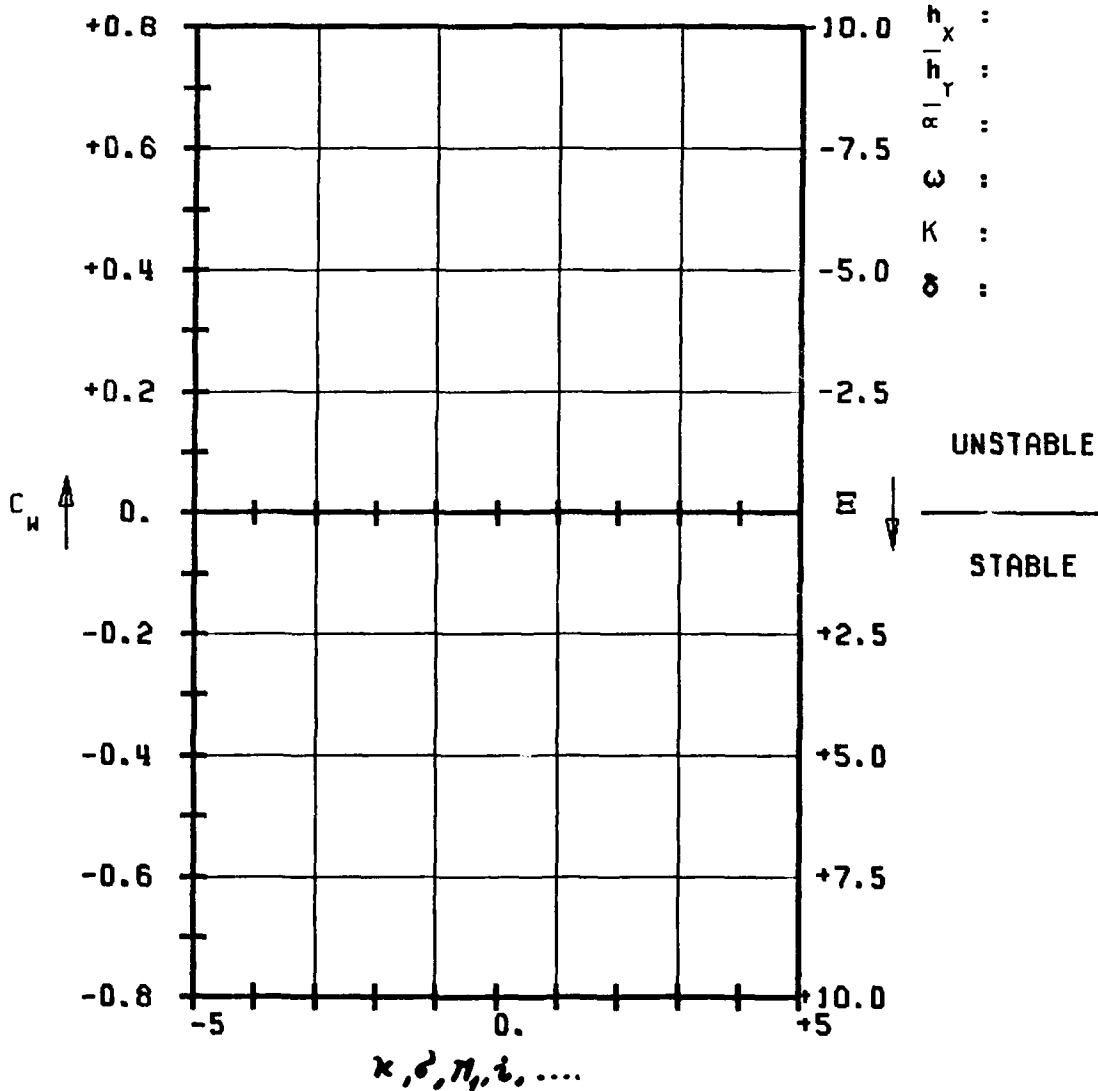


DIAGRAM 4 :

AERODYNAMIC WORK AND DAMPING COEFFICIENTS  
(FOR A RIGID MOTION) IN DEPENDANCE OF FLOW  
QUANTITIES AND CASCADE GEOMETRY.

### 2.3 Theoretical off-design calculations

It is obvious that, for a detailed evaluation of the state-of-art of prediction models for aeroelasticity, several codes must be compared. To this end, 52 institutions have been contacted regarding the off-design calculations of the test cases. Up to now the following 25 persons have announced their participation, each with one or several computing codes (see table 4). The off-design calculations will be performed, as suggested by the Scientific Committee at the Lausanne Symposium on Aeroelasticity in Turbomachines [10], by the participants during 1983, whereafter all the results will be compiled and compared for presentation at the third Symposium on Aeroelasticity, to be held in Cambridge, U.K., in 1984.

Institution	Country	Name	Number of Codes
{Physical Sciences Inc.} {University of Tokyo}	USA Japan	N.H. Kemp H. Shoji }	1
Cambridge University	UK	D.S. Whitehead	4
United Technologies Research Center	USA	J.M. Verdon/ J.M. Caspar	1
United Technologies Research Center	USA	J.M. Verdon	1
University of Tokyo	Japan	S. Kaji	1
ONERA	France	P. Salaün	3
NASA Lewis Research Center	USA	M.E. Goldstein/ W.H. Braun/ F.B. Molls	2
Kyushu University	Japan	M. Namba	1 (??)
Florence University	Italy	F. Martelli	2
Lausanne Inst. of Technology	Switzerland	T.H. Fransson	1
University of Notre-Dame	USA	H. Atassi	?
DFVLR-Göttingen	W. Germany	V. Carstens	?
University of Tennes- see Space Inst.	USA	J. Caruthers	?
Technische Hochschule Aachen	W. Germany	H.E. Gallus/ K. Vogeler	?
Massachusetts Inst. of Technology	USA	E. Crawley	3
Imperial College	UK	M. Graham	?
University of Tennessee Space Institute	USA	M. Kurosaka	?
University of Tokyo	Japan	H. Tanaka	?
University of Tokyo	Japan	Y. Tanida	?
Naval Postgraduate School	USA	M. Platzner	?
Mitsubishi Heavy Ind. Ltd.	Japan	S. Takahara	?

Table 4: Participants in the theoretical part of the work on "Aeroelasticity in Turbomachine-Cascades"

#### 2.4 Initiation of additional experiments in existing test facilities

The observations during the present project have shown that experimental aeroelastic investigations in highly loaded subsonic turbine bladings in plunging and pitching modes are difficult to find in the open literature. To remedy this, the Laboratoire de Thermique Appliquée (LTA) has started such an experimental work. The cascade is currently under fabrication, and it will be instrumented with flush mounted pressure transducers and static pressure tappings towards the end of this year. It is expected that the first aeroelastic results with this cascade will be obtained in March-April 1983, whereafter these data will be distributed as test cases for the off design calculations.

Another lack of well documented experimental data have been found in the supersonic flow regime. It is here well known that the linearized supersonic flat plate theories gives very good agreements with two-dimensional compressor cascade experiments (thin airfoils). However, the validity of the strip theory, i.e. the use of two-dimensional prediction methods in a quasi-two-dimensional or a three-dimensional upstream flow, has never been established in the transonic and supersonic flow regimes, not even for flat plates. Theoretical investigations by Namba [11] indicate that three-dimensional effects in completely supersonic cascades are generally small and the strip theory predicts local as well as integrated aerodynamic forces with good accuracy. In the transonic flow, i.e. in the normal operating range of a modern turboreactor, however, the strip theory approximation breaks down near the sonic span station and three-dimensional effects are of primary importance. An experimental investigation of this phenomena in a quasi-two-dimensional test facility would therefore be of large interest for the development of fan stages in future jet engines.

3. RESEARCH PLANNED FOR THE PERIOD SEPTEMBER 1, 1982 -  
AUGUST 31, 1983

As can be seen from chapter 2, the present project is now well under way.

During the rest of 1982, refinements in the compilation of test cases will be made. These will thereafter be distributed for off-design calculations by several prediction methods towards the end of 1982.

The theoreticians participating in the present work will thereafter "predict" the aeroelasticity of the test cascades. These calculations will all be performed during 1983.

Further, many contacts will be necessary in order to supply the theoreticians with all the information each one need for their prediction methods, as well as to evaluate and compare the different results obtained from the different experiments and theoretical models.

4. FISCAL STATUS FOR THE FIRST YEAR OF THE PROJECT  
September 1, 1981 - August 31, 1982

This chapter is divided into two parts:

- I Coordination of the present joint research project
- II Contributions to aeroelasticity research by LTA

(See Unsolicited Research Proposal - Jan. 1981, chapter 5)

4.1 Coordination of the present joint research project

	AFOSR		Costsharing	
	actual (12 months)	budgeted (12 months)	actual (12 months)	budgeted (12 months)
	US\$	US\$	US\$	US\$
1. Salaries & Wages				
-Principle Investigator P. Suter	---	---	7'000.--	6.600.--
-Research associate T. Fransson	11'200.--	9'700.--	6'500.--	5'000.--
2. Expendible Material & Supplies	---	---	---	---
3. Permanent Equipment	---	---	---	---
4. Travels	---	3'100.--	---	1'800.--
1 trip to Germany (KWU, DFVLR,Th-Aachen)		---	480.--	---
1 trip to G.B. (ASME-Conference, Rolls-Royce, GEC, Central Elec. Gen.Board, Cambridge University)	1'600.--	---	300.--	---
1 trip to France (ONERA)		---	220.--	---
5. Publication, report, initialization of the project Secretary, telex, telephone			2'200.--	1'000.--
6. Other direct costs			3'500.--	5'000.--
7. Indirect costs	---	---	---	---
Total costs	12'800.--	12'800.--	20'200.--	19'400.--
=====				

#### 4.2 Experimental and theoretical aeroelastic investigations at LTA

Approximative 1982 budget of turbomachine section at LTA (for information only)

1. Salaries & Wages	
7 collaborators, about 3,9 man/year	110'000.--
2. Expendable materials	68'000.--
3. Computer time	42'000.--
4. Other direct costs	8'000.--

Approximative 1982 budget of the turbomachine section at LTA

\$ 228'000.--

## 5. CONCLUSIONS

In the first year of the project "Aeroelasticity in Turbomachine-Cascades", a very large interest for the present work have been found to exist both in the academic world as among the manufacturers of turboreactors and industrial turbomachines. Unfortunately, several industrial institutions cannot participate because of the proprietary nature of their work. Still, a large number of experimental data (36 sets) have been put at our disposal for comparison between experimental results and prediction models for flutter and forced vibrations.

Also the theoretical aspects of the comparative work is well represented, as already 25 persons have announced their intentions to participate with one or several prediction methods.

From the large data base of experimental results, a few test cases are currently being compiled for distribution for off-design calculations, and comparisons, towards the end of 1982.

As a part of this compilation, a precise nomenclature and representation format to be used during the present work has been established.

An absence of well documented experimental data have been found, noticably in the domain of high turning subsonic turbine blades and in the field of transonic/supersonic quasi-two-dimensional flat plate investigations. As regards to the high turning turbine blades, the Laboratoire de Thermique Appliquée has recently started such experimental work. The result of this investigation can be distributed, as a further test case, during 1983.

6. REFERENCES

- | 1 | F.O. Carta                    "Unsteady Gapwise Periodicity of Oscillating Cascaded Airfoils"  
*ASME Paper 82-GT-286, 1982*
- | 2 | J.M. Verdon                    "Development of a linear Unsteady Aerodynamic Analysis for Finite-Deflection Subsonic Cascades"  
*AIAA Paper 81-1290, 1981*
- | 3 | Y.C. Fung                    "An introduction to the Theory of Aeroelasticity"  
*Dover Publications, Inc., New-York, 1969, page 82*
- | 4 | H. Ashley  
R.L. Bisplinghoff            "Principles of Aeroelasticity"  
*Dover Publications, Inc., New-York, 1969, page 202*
- | 5 | F.O. Carta                    "Coupled Blade-Disk-Shroud Flutter Instabilities in Turbojet Engine Motors"  
*Journal of Engineering for Power, July 1967, p.p. 419-426*
- | 6 | S.R. Bland  
(Coordinator)                "AGARD Two-Dimensional Aeroelastic Configurations"  
*AGARD Advisory Report No 156, 1979*
- | 7 | T. Fransson  
P. Suter                    "Aeroelasticity in Turbomachine-Cascades" First Semi-Annual Progress Report under Grant AFOSR-81-0251  
*Report EPFL-LTA/TM-4-82*
- | 8 | T. Fransson  
P. Suter  
(Coordinator)                "Two-Dimensional and Quasi-Two-Dimensional Experimental Testcases for Aeroelastic Investigations in Turbomachine-Cascades"  
*Report EPFL-LTA, in preparation*
- | 9 |                                "Aéroélasticité dans les turbomachines"  
*Proceedings of the Symposium held in Paris, France, 1976*  
*Revue Mécanique Française, Numéro spécial 1976*
- | 10 | P. Suter  
(Editor)                    "Aeroelasticity in Turbomachines"  
*Proceedings of the Symposium held in Lausanne, Sept. 8-12, 1980.*

- | 11|    M. Namba            "Three-Dimensional Aerodynamic Characteristics  
          A. Ishikawa       of Oscillating Supersonic and Transonic Annular  
                             Cascades"  
                             *ASME-Paper 82-GT-126 , 1982*
- | 12|    D. Schläfli        "Flutteruntersuchungen an einem transsonischen  
                             Turbinengitter im Ringgitterkanal an der  
                             EPF-Lausanne"  
                             *Report EPFL-LTA/TM-5-82*  
                             *Lausanne, Switzerland, 1982*
- | 13|    W.J. Rakowski       "A Research Program for the Experimental  
                             Analysis of Blade Stability"  
                             *AIAA/SAE - 14 joint Propulsion Conference,*  
                             *Las Vegas, 1978*
- | 14|    M. Kurosaka        "Linear and Nonlinear Analysis of Vortex  
                             Whistle-Another Blade Buster"  
                             *in |10| , pages 443-453*
- | 15|    A. Kirschner        "Control of Vibration in Aeroelastic Cascade  
                             B. Fosco               Experiments"  
                             E. Müller              *in |10| , pages 285-295*
- | 16|    A. Bölcs            "A Test-Facility for the Experimental Inves-  
                             tigation of Steady and Unsteady Flows in Annu-  
                             lar Cascades"  
                             *To be presented at the ASME Gas Turbine Con-*  
                             *ference, 1983.*
- | 17|    T.H. Fransson       "Numerical Experiments with Different Boundary  
                             Conditions in Subsonic Unsteady Flows"  
                             *Presented at "Unsteady Perturbations in Inter-*  
                             *nal Flows" - Cambridge, England,*  
                             *19-20/3 1981*
- | 18|    T.H. Fransson       "Numerische Berechnung der zweidimensionalen  
                             Unterschallströmung in einem oszillierenden  
                             Schaufelgitter"  
                             *Presented at the "Strömungstag an der EPF-*  
                             *Lausanne", Switzerland, 15.01.1982*

## Appendix I

Re: Aeroelastic research work at LTA (Lab. de thermique appliquée)

LTA is working actively in the field of aeroelasticity with two different projects, both of which will be put at the disposal of the workshop:

- experimental flutter research.
- theoretical forced vibration investigations.

### I.I. Experimental work

- The experiments with an annular transonic turbine cascade (12,15,16) have permitted us to observe self-excited blade vibrations in our non-rotating annular test facility. This instability can be classified as shock- and/or stall-induced flutter (see fig. 1).

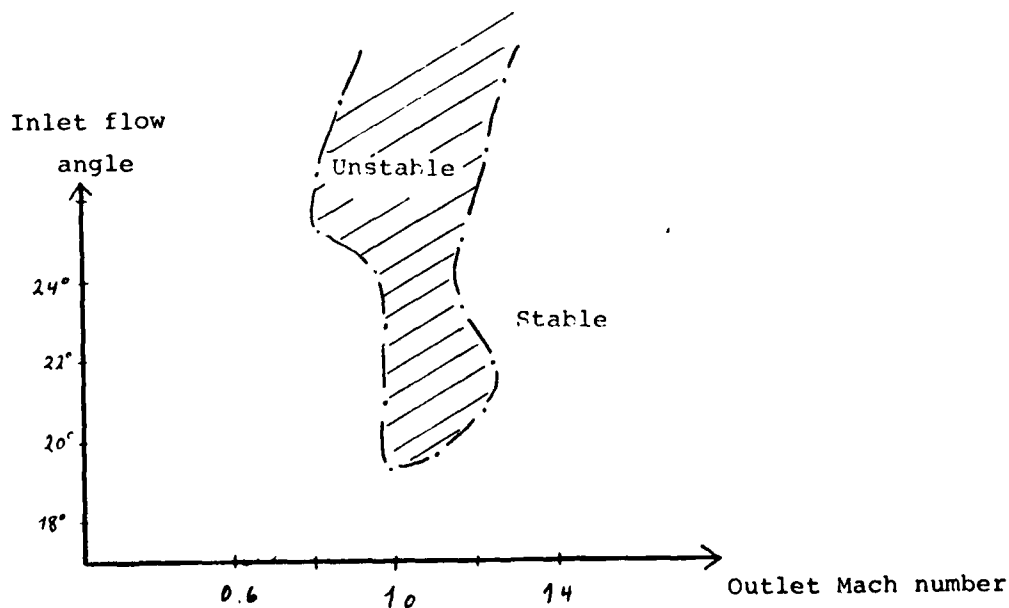


Fig 1: Flutter boundaries for transonic turbine cascade at LTA

It has been found that flutter is an organized movement, in which the amplitude of a certain blade fluctuates in time. It is seen that a continuous energy transport from the first to the second etc. to the last blade in the cascade takes place. This coupling over all blades in an annular nozzle makes it rather unlikely that real flutter conditions may be reproduced in a linear cascade.

At the moment, this transonic turbine cascade is run under forced vibrations. Systematic tests are performed to establish the influence of several important parameters, as for example the interblade phase angle and backpressures, on the aerodynamic stability of the cascade.

As the next step in aeroelastic experiments at LTA, a highly loaded subsonic turbine cascade for forced vibration experiments is under fabrication and will be built into the non-rotating annular test facility. The objectives are threefold:

- + gain experience with a highly loaded subsonic cascade in unsteady motion
- + results for off-design calculations (both for the calculations performed at LTA and for the working group on aeroelasticity in general)
- + compare results obtained in an annular cascade with corresponding ones in a linear cascade. To this end, we are looking for a laboratory equipped with a linear cascade for forced and self-excited vibrations, in order to coordinate our research and perform experiments on an identical cascade.

Among the results to be obtained are:

- + steady and unsteady pressure probe traverses up- and down
- + steady and unsteady pressure coefficients on blades
- + blade vibration
- + visualization in the transonic flow domain (Schlieren)
- + instability dependence on flow conditions, blade-vibrations, interblade phase angle,...

The instrumentation (unsteady flushmounted pressure transducers) will follow later this year, and the first tests are scheduled for March 1983.

- Several other interesting phenomena have been investigated in this annular test vehicle. As an example can be mentioned that, in certain flow domains, the same "Vortex Whistles" as was noticed in the annular test rig at General Electric Co, appeared also in our nozzle ( [13] , [14] )  
In our case, this problem could be remedied simply by reproducing the same flow conditions with another setting of the upstream swirl vanes.
- Experimental investigations on blade vibrations due to random fluctuations of the upstream flow conditions are also under way at LTA. These tests are performed on highly loaded subsonic turbine blades in a linear cascade.

Among the most interesting results can be mentioned:

- + Miniaturized pressure transducers mounted on the blades indicate a high correlation between the blade movement and the pressure variation in the attached flow region.
- + In the detached flow domain, however, the pressure fluctuations do not show a correlation with the blade movement.
- + A high upstream flow turbulence excites the blades into a much larger amplitude than a lower turbulence level.

### I.II. Theoretical work

A numerical code for predicting instabilities in a subsonic cascade with vibrating blades is being developed at the LTA. This work has shown that the inlet and outlet boundary conditions may influence the unsteady flow in the cascade to a large extent. Some results of this calculations have been represented in a movie film, showing clearly how the pressure waves created at the vibrating blades travel up - and downstream, and how they interfere with the upstream and downstream boundaries ( /6/, /7/ ). The code is currently being changed to allow better for higher stagger angles and thicker blades. This improvement is judged necessary in order to correctly handle the unsteady flow in the leading and trailing edge regions.

I.III Scientific reports since the submission of the research  
proposal on January 9, 1981

- A. Bölcs "Berechnung der Strömung in einem Ueberschall-  
angeströmten Schaufelgitter bei variabler  
Schichtdicke"  
*ZAMP Vol. 32.1981*
- A. Bölcs "Charakteristikenverfahren für quasi-  
dreidimensionale und anisentrope Ueber-  
schallströmungen"  
*Presented at "Strömungstag an der EPFL"  
Lausanne, Switzerland, 15.01.1982*
- T. Fransson "Numerical Experiments with Different Boun-  
dary Conditions in Subsonic Unsteady Flows"  
*Presented at "Unsteady Perturbations in Inter-  
nal Flows"  
Cambridge, England, 19/20.3.1981*
- T. Fransson "Numerische Berechnung der zweidimensionalen  
Unterschallströmung in einem oszillierenden  
Schaufelgitter"  
*Presented at "Strömungstag an der EPFL"  
Lausanne, Switzerland, 15.01.1982*
- A. Bölcs "Experience with Turbine and Compressor  
A. Mathys Cascades in an Annular Test Facility"  
*Proceedings of Symposium on "Measuring Tech-  
niques in Transonic and Supersonic Cascades  
and Turbomachines",  
Lyon, France, 1981*
- D. Schläfli "Flutteruntersuchungen an einem transsonischen  
Turbinengitter im Ringgitterkanal an der  
EPF-Lausanne"  
*Report EPFL-LTA/TM-5-82, Lausanne, Switzerland  
1982*
- T. Fransson "Ablöseverhalten eines Kreisbogenprofiles  
bei variabler Reynoldszahl und variablem  
Anströmwinkel"  
*Report EPFL-LTA/TM-1-82*
- P. Testori "Etude d'écoulement autour d'une aube isolée  
A. Schiess en régime transsonique (Diplôme 1981)"  
*Report EPFL-LTA, 1981*

- F. Beretta-Piccoli      "Versuche mit einem Radialverdichter-  
A. Böls                      Vorschalttrad: 2. Schlussbericht"  
*Report EPFL-LTA/TM-6-82*
  
- T. Fransson                "Charasteristics of Aerodynamic Five-  
O. Sari                      Hole-Probes in Transonic and Supersonic  
                                 Flow Regimes"  
*Proceedings of "Measuring Techniques  
in Transonic and Supersonic Cascades and  
Turbomachines"*  
*Lyon, France, 15/16.10.81*
  
- F. Beretta-Piccoli        "Probe Investigations in the Proximity  
T. Fransson                of a Wall in Supersonic Flow"  
*Proceedings of "Measuring Techniques  
in Transonic and Supersonic Cascades and  
Turbomachines"*  
*Lyon, France, 15/16.10.81*
  
- X.C. Lian                  "Visualisation de l'écoulement de surface  
                                 sur un profil"  
*Report EPFL-LTA/TM-2-82*
  
- O. Sari                      "Eichung der Aerodynamischen Sonde R 18"  
F. Beretta-Piccoli        *Report EPFL-LTA/TM-3-82*  
T. Fransson
  
- T. Fransson                "Aeroelasticity in Turbomachine-Cascades"  
P. Suter                      First Semi-Annual Progress Report  
*Report EPFL-LTA/TM-4-82*
  
- T. Fransson                "Ablöseverhalten eines Kreisbogenprofiles  
X. C. Lian                    bei variabler Reynoldszahl und variablem  
                                 Anströmwinkel"  
                                 (Nachtrag zum Bericht LTA-TM-1-82)  
*Report EPFL-LTA/TM-7-82*
  
- T. Fransson                "Aeroelasticity in Turbomachine-Cascades"  
P. Suter                      Second Semi-Annual Progress Report  
*Report EPFL-LTA/TM-8-82*

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